COMPARISON OF ELECTROCARDIOGRAMS AND VECTORCAR-DIOGRAMS IN CONGENITAL AORTIC STENOSIS*†

BY

RAUL GAMBOA, PAUL G. HUGENHOLTZ, AND ALEXANDER S. NADAS

From the Sharon Cardiovascular Unit, Children's Hospital Medical Center, Department of Pediatrics, Harvard Medical School, Boston, Massachusetts, U.S.A.

In a previous study (Hugenholtz, Lees, and Nadas, 1962) correlations between the resting hæmodynamic state in congenital aortic stenosis (AS) and the cube vectorcardiogram showed great accuracy in predicting the presence of left ventricular hypertension. Results were better than those obtained by the standard electrocardiogram in a study of a larger group of similar patients (Braunwald *et al.*, 1963). Furthermore, alterations in the direction and magnitude of specific QRS vectors, as projected on the horizontal plane, correlated to some degree with left ventricular peak pressure and aortic gradient. However, the wide variation in these measurements often made proper assessment of the individual case impossible. Thus, while distinctly better than the standard electrocardiogram in the recognition of left ventricular hypertension, this type of uncorrected vectorcardiographic recording still proved to be inferior to the assessment of severity obtained by means of cardiac catheterization.

The lead system proposed by Frank (1956) possesses characteristics which, on theoretical grounds, would make it a more desirable system for registration of the "equivalent dipole" (Langner *et al.*, 1958). In practical terms it has confirmed these expectations in sharper delineation of the normal (Hugenholtz and Liebman, 1962), in improved accuracy in the necropsy confirmed diagnosis of various myocardial disorders (Hugenholtz, Forkner, and Levine, 1961), and in the assessment of left and right ventricular hypertension in patients with congenital aortic and pulmonic stenosis (Hugenholtz and Gamboa, 1964). It appeared timely therefore to compare its usefulness to that of the standard electrocardiogram and the cube vectorcardiogram obtained simultaneously in the same patient.

The availability of detailed hæmodynamic data such as left ventricular peak systolic pressure, aortic valve gradient, stroke work, and valve area, suggested the study of these factors and their relation to electrical depolarization. The age-groups studied (5 to 21½ years) appeared particularly useful since complicating factors such as conduction defects or coronary artery disease were absent. Heart weight or wall thickness at necropsy, the traditional yard-sticks, which in previous studies had shown a less than satisfactory correlation with the cardiogram (Griep, 1959; Scott, 1960; Selzer *et al.*, 1958), were not analysed.

† Since this paper was prepared for press, the authors have drawn attention to an error in calibration which necessitates multiplying all voltage measurements by a constant factor of 1·41. *Editor.*

SUBJECTS AND METHODS

Thirty patients with congenital aortic stenosis were selected from consecutive admissions studied at the Cardio-Pulmonary Laboratory of the Children's Hospital Medical Center: their ages varied from 5 to 21½ years and all but one were male. Electrocardiographic and vectorcardiographic studies were obtained immediately before or on the day after cardiac catheterization. In 4 patients studies were done during catheterization. All studies were carried out under resting circumstances. In 14 instances pressure recordings and cardiac output determinations were also made during bicycle exercise in the supine position. Vectorcardiograms were monitored continuously in three of these studies.

A second group of 20 patients in whom similar data were available (4 were female) was also included to augment the material for statistical purposes. Thus some of the conclusions are extended to a total of 50 patients in whom either cube or Frank vectorcardiographic data are available. Since, in this larger group, these measurements were not obtained each time in the same patient, no detailed data are tabulated, though they are available upon request to the authors. The range of normal vectorcardiographic measurements has been given before (Hugenholtz and Liebman, 1962).

Cardiac catheterization of the right side of the heart was carried out in the usual fashion in all 50 patients, while the left side of the heart was entered by the retrograde technique in all but 3: in 2 of these the transseptal approach and, in the remaining, the percutaneous technique with general anæsthesia were used. Details of the methods employed in deriving the hæmodynamic data and the calculation have been given elsewhere (Hugenholtz and Gamboa, 1964). Similarly a minute description of the vectorcardiographic technique and the computation of these data are given in the report indicated. In brief, the magnitude of the maximum spatial voltage (MSV) was derived by Pythagoras theorem, $MSV = \sqrt{x^2 + y^2 + z^2}$, where x, y, z represent the transverse, vertical, and sagittal components of that vector. The sum of selected spatial vectors (SMSV) was obtained by adding the magnitude of the MSV to that of the vector occurring 0·01 second before and to those occurring 0·01 and 0·02 second after the maximum vector. The spatial QRS–T angle was derived from Helm and Fowler's formula (1953),

$$Cos\ \theta = \frac{(A^x QRS \times T) + (A^y QRS \times T) + (A^z QRS \times T)}{A\ QRS \times T},$$

where x, y, z represent the 3 orthogonal projections of the maximal spatial QRS and T vectors and A QRS × T those vectors themselves.

RESULTS

Detailed hæmodynamic, vectorcardiographic, and electrocardiographic data in the 30 patients who form the nucleus of this study appear in Table I. Although multiple correlations were carried out only selected results are commented upon.

Left ventricular peak systolic pressure, under resting circumstances, varied from a normal range around 100 mm. Hg to 250 mm. Hg. During exercise, in 14 patients, considerable rises in peak pressures, up to 240 mm. Hg, were recorded. Vectorcardiograms during these studies did not show any change in direction or magnitude of QRS vectors despite the fact that left ventricular peak systolic pressure in Patient No. 12 nearly doubled. The only significant change was an increase in the spatial QRS–T angle in 2 patients.

A significant relation was found between the left ventricular peak systolic pressure (LVPP) and the magnitude of the maximum spatial vector (MSV) as measured by the Frank system (r=0·88; p<0·001, standard error of estimate (SEE)=20 mm. Hg). The regression equation reflecting this relation is LVPP=40·50 mV+75·65. Similar calculation for MSV derived by the cube system was r=0·72; p<0·001, SEE=29 mm. Hg, while for the sum of S in V2 and R in V5, obtained from the standard electrocardiogram, r=0·48, p<0·01, SEE=39 mm. Hg (Fig. 1). Individual correlations of LVPP with the height of the R wave either in V5 or in V6 alone gave still lower coefficients (r=0·42 and 0·40). Consequently these parameters were omitted from further correlations.

When these relationships were studied in the larger and non-identical groups in 50 patients, the LVPP–MSV (Frank) correlation coefficient became 0·85; p<0·001, SEE=19 mm. Hg, while the LVPP–MSV (cube) coefficient was 0·75 p<0·001, SEE=22 mm. Hg. The correlations of LVPP and the sum of SV2+RV5 in this larger group changed little, r=0·49, p<0·01, SEE=40 mm. Hg.

TABLE I

HÆMODYNAMIC DATA AND VECTOR AND ELECTROCARDIOGRAPHIC DATA IN ASSESSMENT OF

Patient No.* and age (yr.)		BSA/ m.2	Cardiac index (l./min./ m.2)	Heart rate	Stroke index/ ml./ beat/m.2	LVPSP (mm. Hg)		Gradient (mm. Hg)		Aortic valve area		Stroke work	
						Rest	Exercise	Rest	Exercise	(cm.2/ pat)	(cm.2/ m.2)	(kgM/ min.)	(kgM/ min./ m.2)
1	10	1·32	3·5	70	50	105	130	20	40	1·25	1·00	6·556	4·967
2*	11½	1·56	6·1	70	87	108	130	12	26	2·00	1·79	12·978	8·319
3	12	1·25	4·6	57	81	112	112	12	22	2·00	1·60	12·294	9·835
4	12½	1·42	3·8	80	47	115	150	22	40	2·41	1·70	7·567	5·329
5	15½	1·65	5·4	68	79	115	145	20	36	2·20	1·33	14·779	8·957
6	11	1·13	6·6	84	79	118	—	14	—	2·00	1·77	10·134	8·968
7	21½	1·88	5·7	96	60	120	190	5	50	2·20	1·17	14·792	7·868
8	5½	0·68	4·4	94	47	120	—	44	—	0·59	0·87	4·540	6·677
9	11½	1·32	3·8	80	48	122	156	36	76	1·10	0·77	8·222	6·229
10	20	1·74	3·9	76	51	130	220	36	106	3·00	1·36	9·400	5·402
11	8	0·92	3·6	88	41	132	—	40	—	0·91	0·99	5·153	5·601
12	14	1·35	5·1	91	56	137	240	40	140	1·00	0·74	12·561	9·304
13	14	1·50	4·9	85	58	140	160	40	64	1·56	1·04	11·160	7·440
14	9	1·20	4·2	96	44	140	—	60	—	0·64	0·53	6·095	5·079
15	18	1·65	4·4	70	63	148	—	32	—	1·55	0·94	14·480	8·778
16	10	1·01	3·6	90	40	148	—	66	—	0·71	0·71	10·602	10·602
17	15	2·14	4·0	88	45	160	175	60	—	1·45	0·70	15·128	7·069
18	11	1·22	5·5	72	76	180	—	76	—	1·22	1·00	13·461	11·034
19	8½	1·05	3·6	88	41	180	180	60	93	0·54	0·53	7·437	7·083
20†	12	1·25	5·3	105	51	195	—	110	—	0·80	0·64	6·283	5·026
21	16	2·30	4·3	80	54	200	—	60	—	1·10	0·48	18·462	8·027
22	12	1·50	6·6	80	82	200	—	82	—	1·23	0·81	23·520	15·682
23	12	1·77	3·7	96	39	205	—	120	—	0·61	0·34	10·120	5·718
24	12	1·13	4·8	105	46	208	—	115	—	0·48	0·42	9·420	8·336
25	8½	1·18	4·3	105	41	208	240	152	154	0·40	0·34	8·433	7·147
26	20	1·92	4·2	80	53	216	—	134	—	0·71	0·37	21·309	11·098
27	7½	0·90	2·6	90	29	220	240	120	160	0·32	0·36	4·650	5·167
28	12	1·23	3·4	84	39	240	—	150	—	0·33	0·27	12·583	10·230
29†	16	1·67	4·9	82	60	250	—	148	—	0·75	0·45	24·089	14·425
30‡	5	0·70	3·5	135	26	138	—	58	—	0·40	0·50	—	—

* All patients except No. 2 were male.
† Transseptal technique.
‡ Percutaneous technique.

When the peak systolic gradient was correlated with the MSV, the Frank vectorcardiographic data yielded a coefficient of 0·80, p<0·001 (in the larger group, r=0·82; p<0·001, SEE=20 mm. Hg), while for the cube data the coefficient was 0·73, p<0·001 (r=0·75; p<0·001, SEE=30 mm. Hg in the larger group). The correlation with SV2+RV5 gave an r value of 0·42, while for the total 50, r increased slightly to 0·45, p<0·01.

Applying the sum of selected vectors as described, the correlation coefficient with peak pressure was 0·75, p<0·001, SEE=22 mm. Hg from the cube data, while an r value of 0·89; p<0·001, SEE= 15 mm. Hg, was obtained from the Frank data. The regression equation for the latter is LVPP= 23·55 mV+44·25 (Fig. 2). These figures were also calculated for the larger group of 50 patients and were 0·77, p<0·001, and 0·90, p<0·001, SEE=15 mm. Hg, respectively.

Stroke work, corrected for body surface area, was also correlated with the SMSV; the coefficient for the Frank system was 0·30, p<0·5, for the cube system 0·25, p<0·5, and for the sum of SV2 and RV5, r=0·05.

LEFT VENTRICULAR HYPERTROPHY IN CONGENITAL AORTIC STENOSIS

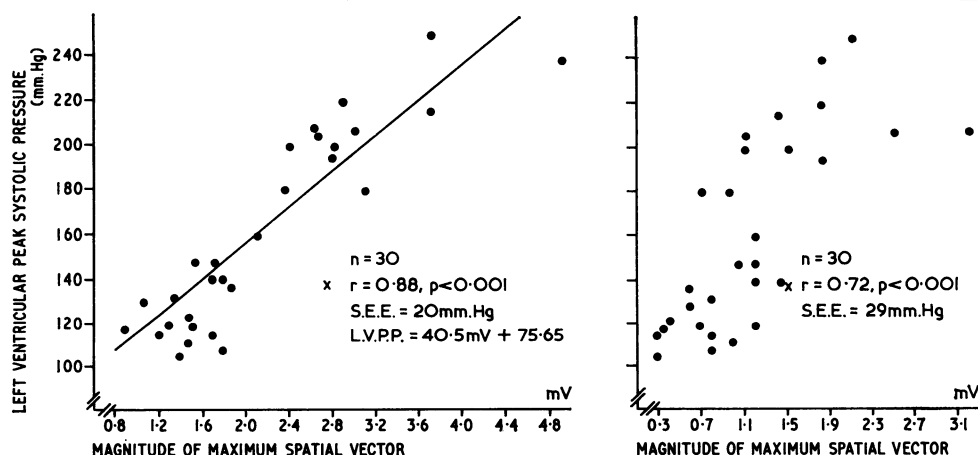| Frank Magnitude of spatial vector				Cube Magnitude of spatial vector			Spatial QRS–T angle	SV2	RV5	Sum SV2 and RV5	ST–T change
Max.	0·01 sec.	0·02 sec.	Sum of vector	Spatial QRS–T angle	Max.	Sum of vector					
1·40	0·33	0·52	3·05	23°	0·30	0·88	22°	18	26	44	—
1·80	0·12	0·24	3·50	18°	0·80	0·98	20°	20	27	47	—
1·47	0·17	0·33	3·30	35°	1·00	2·10	40°	16	18	34	—
1·20	0·30	0·54	3·50	20°	0·30	0·80	25°	16	18	35	—
1·70	0·30	0·50	3·10	15°	0·80	2·50	20°	16	26	42	—
0·88	0·10	0·21	3·20	32°	0·35	0·80	40°	12	24	36	+
1·51	0·16	0·30	3·50	40°	0·70	0·85	38°	20	9	29	—
1·30	0·30	0·60	3·25	35°	1·20	2·30	40°	16	26	42	—
1·46	0·21	0·43	4·00	44°	0·40	0·89	44°	18	18	36	+ + +
1·06	0·04	0·25	4·10	45°	0·60	2·10	50°	31	13	44	+ + +
1·34	0·24	0·44	4·50	41°	0·80	2·50	40°	28	32	60	+
1·86	0·29	0·36	4·93	45°	0·60	2·10	38°	30	35	65	+
1·70	0·22	0·50	4·50	30°	1·45	3·50	25°	5	22	27	—
1·76	0·09	0·23	4·75	99°	1·20	3·50	80°	13	35	48	+
1·53	0·04	0·13	4·50	61°	1·20	3·60	50°	22	28	50	+
1·72	0·09	0·23	3·75	20°	1·06	3·10	35°	20	14	34	—
2·11	0·18	0·19	4·00	90°	1·20	2·95	60°	17	13	30	—
2·35	0·22	0·58	4·75	32°	0·70	2·00	30°	19	28	47	—
3·12	0·17	0·31	7·00	75°	0·96	2·50	78°	28	33	61	+ +
2·80	0·12	0·31	6·00	112°	1·82	3·70	100°	30	30	60	+
2·40	0·21	0·26	6·35	20°	1·10	3·80	20°	12	34	46	+ +
2·80	0·12	0·22	5·75	80°	1·50	3·30	70°	24	26	50	+
2·64	0·17	0·46	6·69	140°	1·10	3·60	100°	16	38	54	+ + +
2·62	0·17	0·79	6·50	12°	2·50	5·50	17°	26	26	52	+
3·60	0·21	0·67	7·25	110°	3·20	6·00	120°	24	32	56	—
3·70	0·19	0·36	6·75	90°	1·40	3·40	30°	18	17	35	+
2·88	0·31	0·81	8·00	100°	1·80	3·20	90°	28	22	50	+ +
4·92	0·12	0·81	9·00	45°	1·80	3·60	40°	26	28	54	+
3·68	0·29	0·50	8·50	175°	2·10	5·70	150°	26	34	60	+ +
2·76	0·21	0·78	6·00	100°	1·50	2·80	100°	23	35	58	+

FIG. 1.—Relation between magnitude of maximum spatial vector and left ventricular peak pressure in 30 patients with aortic stenosis. Frank system (left), cube system (right). The X indicates patient No. 30 studied during general anæsthesia.
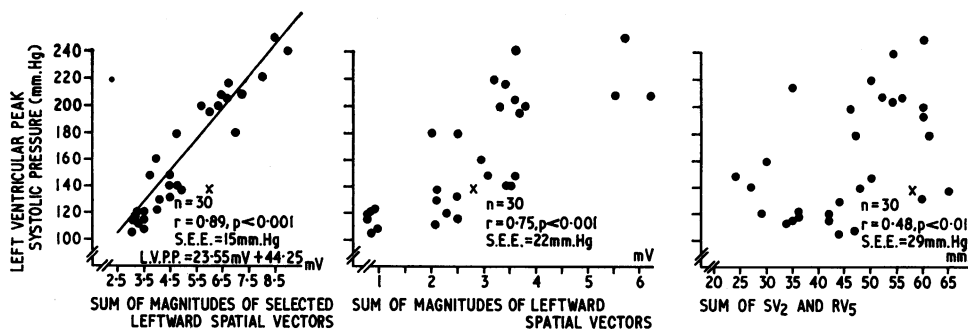
FIG. 2.—Relation between the sum of selected QRS vectors as derived from the Frank system (left), cube system (middle), SV2+RV5 (right), and left ventricular peak pressure in 30 patients with aortic stenosis.
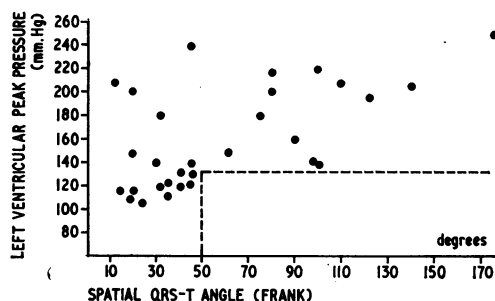

FIG. 3.—Relation of spatial QRS–T angle, as derived from the Frank system, and left ventricular peak pressure in aortic stenosis.

Figure 3 illustrates the distribution of the spatial QRS–T angle derived by the Frank system and its relation to peak pressure. The significance of this correlation lies only in the fact that angles of 50 degrees or more were never seen with ventricular pressures below 135 mm. Hg, whereas normal as well as wide spatial QRS–T angles were observed with peak pressures in excess of 135 mm. Hg. Similar analysis of data recorded by the cube system was less significant. The projection of the maximum spatial QRS vector on the frontal plane indicated a narrow range between $+80°$ and $+10°$ and was not useful in a diagnostic sense. Findings from the cube system or the
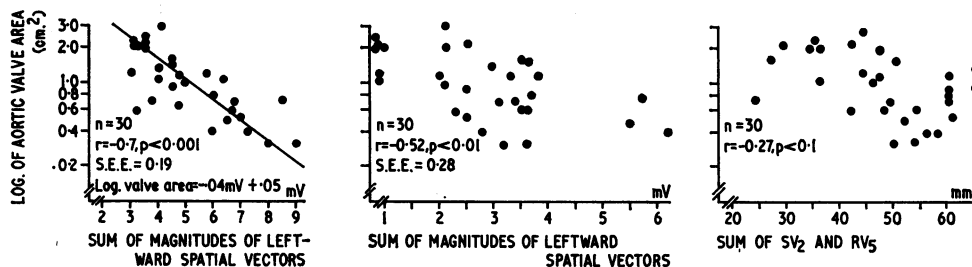

FIG. 4.—Correlation between valve area and the sum of selected QRS vectors derived by the Frank system (left), cube system (middle), and SV2+RV5 (right), in 30 patients with aortic stenosis.

standard electrocardiogram showed a slightly wider range, from $+90°$ to $-15°$, however; these differences were also not significant.

The valve area was related to the sum of selected QRS vectors derived both by the Frank and cube systems and also to the sum of SV2 and RV5: this relationship is shown in Fig. 4. There was a significant inverse relationship with the measurements made by the Frank system ($r = -0.70$, $p < 0.001$, SEE$= 0.19$), and the regression equation is expressed as log. valve area $= -0.04$ mV $+0.05$. Less significance could be given to the correlation coefficients derived by the cube system ($r = -0.52$, $p < 0.01$) and the standard electrocardiogram ($r = -0.27$, $p < 0.1$).

Some of the discrepancies observed between the recordings obtained from the various lead systems are further illustrated in Fig. 5, 6, and 7.
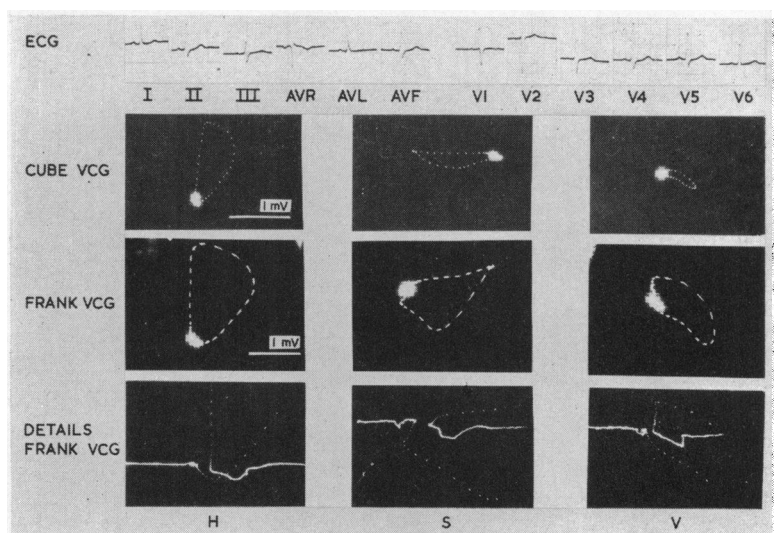
FIG. 5.—J.B., 15-year-old boy. Left ventricular peak pressure 160 mm. Hg, aortic gradient 60 mm. Hg, and aortic valve area 1·45 sq. cm. Note posterior displacement of the QRS loop, increased maximum spatial voltage, and reduced initial forces in both vectorcardiographic systems. The electrocardiogram is normal by voltage criteria.
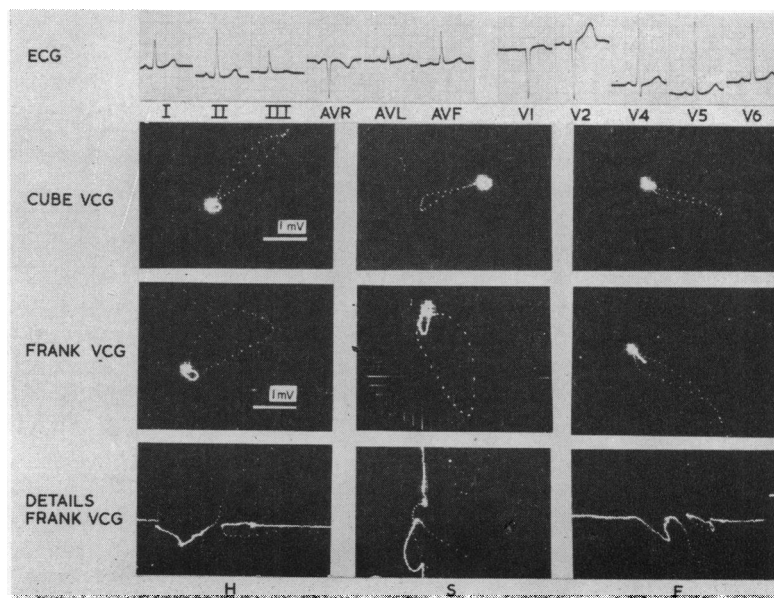

FIG. 6.—R.R., 8½-year-old boy. Left ventricular peak pressure 208 mm. Hg, aortic gradient 152 mm. Hg, aortic valve area 0·40 sq. cm. Posterior displacement of the QRS loop, increased maximum spatial voltage, and reduced 0·01 and 0·02 second vectors in both Frank and cube systems. The QRS–T spatial angle is abnormal in both systems. The electrocardiogram is diagnostic of left ventricular hypertrophy by voltage criteria; the T waves are normal.
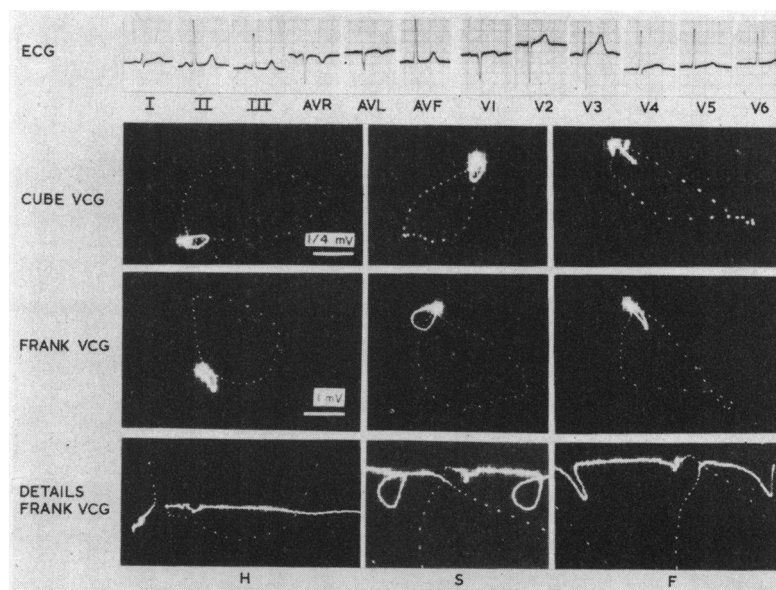
FIG. 7.—M.S., 20-year-old youth. Left ventricular peak pressure 216 mm. Hg, aortic gradient 134 mm. Hg, aortic valve area 0·71 sq. cm. Posterior displacement of the QRS loop, increased maximum spatial voltage, and reduced 0·01 and 0·02 second vectors in both vectorcardiographic systems. However, the Frank system shows an abnormal QRS–T spatial angle (90°), while this angle is normal with the cube system. The electrocardiogram is normal by voltage criteria.

DISCUSSION

Although electromotive forces generated by the myocardium have long been thought to reflect certain aspects of ventricular function, a direct linear relation between left ventricular peak pressure and events recorded in the electrocardiogram has thus far not been shown. In fact, the partially accepted concept of Cabrera and Monroy (1952) regarding specific electrocardiographic differences in "systolic" versus "diastolic" overloading, has recently been challenged by Selzer et al. (1962) in a series of patients studied at necropsy. Furthermore, in a comprehensive review of 100 patients with congenital aortic stenosis, Braunwald and co-workers (1963) were unable to find a significant relation between the electrocardiogram and the hæmodynamic state. More recently, the use of new vectorcardiographic criteria (Hugenholtz et al., 1962) and the application of a corrected lead system (Hugenholtz and Gamboa, 1964) have altered these views and have permitted the recording of a specific relation between pressure and certain spatial QRS forces, albeit a different one from that indicated by the Mexican group.

The data from this study further indicate that, in this type of patient, QRS forces, when recorded by a corrected lead system, reflect intraventricular peak systolic pressure much more accurately (r=0·89) than when they are derived by means of the "uncorrected" cube system (r=0·75) or the electrocardiogram (r=0·48). Thus, the method by which the electrical events are recorded constitutes an essential difference. Correlation coefficients obtained with this corrected lead system are not only consistently higher for all parameters studied (Fig. 1 and 4), they are also closer to those obtained in the larger group of patients (r=0·90 and 0·77 respectively for Frank and cube data), proving that the statistical advantage of studying a larger number of patients (n=50) did not result in a significant improvement. Furthermore there is a marked reduction in the standard error of the estimate from 29 to 22 and 15 mm. Hg respectively for electrocardiogram, cube, and Frank data. This latter measurement reflects a reasonable accuracy in the prediction of the individual hæmo-

dynamic measurement and thus, in practical terms, may be the most important reflection of the clinical usefulness of this type of measurement.

This study further confirms observations made earlier, that left ventricular peak systolic pressure is the hæmodynamic parameter yielding the highest correlation (Hugenholtz and Gamboa, 1964). Aortic valve gradient, valve area, and ventricular stroke work, in that order, gave coefficients of much less significance. These findings parallel studies in the isolated heart preparation, which show that myocardial oxygen consumption rises in a linear fashion with increased intraventricular pressure, whereas an equivalent augmentation of stroke volume results in insignificant changes in myocardial oxygen consumption (Monroe, 1964). Though the findings in the present study may not directly relate to this type of experimental evidence, the fact that stroke work has such a low degree of correlation, while peak pressure yields a high degree of correlation, must indicate that the production of resting ventricular systolic pressure is a dominant factor relating to the electromotive forces. These observations further indicate that the resting peak pressure may be at least as sensitive a parameter of left ventricular hypertrophy as are the usual criteria such as heart weight, heart size, or wall thickness.

At the same time, it has been pointed out earlier (Hugenholtz and Gamboa, 1964) that ventricular systolic pressure must be measured under truly resting circumstances and not be augmented by tachycardia or exercise, or altered pharmacologically by anæsthetic agents. The former is shown in Table I where left ventricular peak pressure during exercise rose conspicuously and in not one instance correlated with the MSV or SMSV, as it had done during rest. The latter point is illustrated by patient No. 30 (identified by an X in Fig. 1 and 2) whose LVPP fell far below the regression line and who was the only patient studied while under nembutal anæsthesia. This patient's aortic valve area, plotted against the measured MSV and SMSV, fell exactly on the regression line shown in Fig. 3. This suggests that the low cardiac output was related to the anæsthetic agent and resulted in an artificially lowered intraventricular pressure. These examples illustrate the fact that the measurement made by the MSV and SMSV can only be applied to the estimation of the average intraventricular systolic pressure.

The reasons for the differences between the Frank lead system and the cube system or the standard electrocardiogram are manifold (Fig. 5, 6, and 7, and Table I). The most significant of these is the concept of "lead strength" introduced by Burger and Van Milaan (1946, 1947, 1948), which in turn relates to Wilson *et al.*'s (1944) application of Poisson's integral to the heart. Wilson and co-workers stated in 1944 "the magnitude of the contribution made by the potential variations of any given surface element is large, if its distance from the electrode is small, and vice versa; in fact, it varies roughly as the inverse cube of this distance". This indicates a different strength for each unipolar præcordial lead, a factor often overlooked by those who feel that there is little difference between the electrocardiographic lead systems. A second error, frequently made, is the assumption that anatomical lead axes are identical with electrical lead axes. Schmitt and Simonson (1955) and Pipberger (1958) have pointed to these differences between lead systems and to the necessity of identical "effective lead axes". Since Frank's design, in addition to correcting the former, also creates a near infinite distance of the exploring electrodes to the electrical source or sources, the maximum spatial vector derived in this manner is in effect a measurement of the dipolar component of the heart, if the latter is considered as an electrical generator. Non-dipolar content of body surface potentials, due either to dipole mobility or to multiple current sources of higher singularity, is unlikely to be present, particularly in congenital aortic stenosis with its usual absence of conduction defects in the younger age-group studied here. Even if current dipoles originate during the early depolarization phases, when the right ventricle contributes its forces predominantly they appear to be insignificant due to the stronger cancellation effect produced by the increased left ventricular potentials. Since all measurements made in this study occurred in the mid portion of the QRS complex, even the "advantage" of recording of proximity effects, which may be ascribed to the cube system as well as to the standard electrocardiogram, disappears in the face of the capability of the corrected lead system to register accurately the dipolar component of the hypertrophied left

ventricle.   These three factors then, lead strength, lead direction, and "infinite" distance, controlled and corrected by the design of Frank's lead system, must be held responsible for its superior performance in assessing ventricular peak pressure, as it is reflected in the altered myocardial electrical activity.

Since the cube recording system assumes for each lead a geometrical equidistant position to the centre of electrical activity, without any correction for the variation in the configuration of the chest, dipole eccentricity, as well as other factors, the discrepancies between the Frank and cube systems can be easily understood.   Futhermore, the lack of orthogonality and the extreme variations in lead strength and direction (Langer *et al.*, 1958; Schmitt and Simonson, 1955), particularly along the antero-posterior axis, prevent the accurate calculation of spatial components.   At the same time, it should be pointed out that this study confirmed the previously shown superiority of the cube system over the standard electrocardiogram (Hugenholtz *et al.*, 1962) in the assessment of left ventricular hypertension (Fig. 2).   The poor performance of the latter is not surprising in view of extensive previous work (Braunwald *et al.*, 1963; Selzer *et al.*, 1958) showing its unreliability in the presence of left ventricular hypertrophy.   Furthermore, the voltage criteria for the diagnosis of left ventricular hypertension do not adequately separate the normal from the abnormal electrocardiogram.   Walker and Rose (1961) found that the range of the sum of SV2 and RV5 varied from 15 up to 65 mm. in 849 normal subjects.   The experience at our laboratory is similar.   Thus, the relative merits of these recording systems can be rephrased in stating that the cube system permits the diagnosis of left ventricular hypertrophy quite accurately but its severity expressed as resting elevated peak pressure can only be assessed by the Frank lead system, while the electrocardiogram must be considered unreliable in the assessment of either.

The presence of inverted T waves in lead V5 or V6, or the calculation of a wide QRS–T angle, has always been regarded as an ominous sign in aortic stenosis (Nadas, 1963).   Since they were present in only 18 of the 30 patients, 7 of whom had left ventricular systolic pressure less than 150 mm. Hg, they did not always accurately indicate the severity of left ventricular hypertension.   This led to the determination of the spatial QRS–T angle from the Frank data as shown in Fig. 3.   Not only was there a wide range of distribution, but no significant correlation with peak pressure could be determined.   Although patients with peak pressures less than 135 mm. Hg were never found to have an angle of 50° or more, normal spatial QRS–T angles were seen with peak pressures in excess of 200 mm. Hg.   Thus, even when calculated in spatial terms, QRS–T angles do not appear to be a reliable measurement in the estimation of the severity of left ventricular hypertension.   On the other hand, the presence of a spatial angle in excess of 50° always reflected a pressure in excess of 135 mm. Hg.   Thus, as a parameter related to the hæmodynamic state, it has only supporting significance, and the correlation with either MSV or SMSV proved far more specific.

During exercise, the LVPP increased in two patients from 130 and 137 mm. Hg to 220 and 240 mm. Hg, respectively.   With this change in pressure, there were no changes in the QRS complex observed, but there was a widening of the spatial QRS–T angle with development of abnormal T waves in V5 and V6.   In 12 other patients studied during exercise (Table I), varying increases in peak pressure were observed.   In none were there significant changes in the QRS or T forces.   These findings again support the concept that increased magnitude of the QRS loop in this patient group represents the result of long-standing pressure work (Grimm, Kubota, and Whitehorn, 1963).   Superimposed acute changes in pressure and in wall tension which developed during exercise do not appear to change left ventricular depolarization.   On the other hand, the changes observed in the spatial QRS–T angle in a few cases may indicate that ventricular repolarization does respond to acute hæmodynamic changes.   However, the lack of change in the majority of the group points again to the unreliability of T wave changes as a sign of severity.

The fascinating observations by Grimm *et al.* (1963), in experimentally induced cardiomegaly in rats, shed some light on the mechanisms underlying the strong relation between resting ventricular systolic pressure and the electromotive depolarization forces.   They found that in experimentally induced hypertrophy increases in myocardial cell mass occurred while the design of the individual

sarcomeres remained constant. Increases in the length of the fibre were accomplished by the addition of sarcomeres in series, each of the individual units remaining the same, while increases in tension production were achieved by a greater cross-sectional area. Thus, Linzbach's (1960) histological concept of an increase in number of units of similar size in the human heart constantly required to deliver augmented pressures appears to be valid. The augmented spatial voltages would reflect an increase in the number of such units, though an increased current field originating from the larger cell membrane surface of hypertrophied cells may be another possibility.

Many authors (Wallace, McCall, and Estes, 1962; Bristow, Porter, and Griswold, 1961; Yano and Pipberger, 1964; Toole, van der Groeben, and Spivack, 1962) have attempted to relate one or more parameters, which are altered in hypertrophy of the left ventricle, to a variety of vectorcardiographic parameters obtained by the Frank system. Their data are difficult to compare directly with those obtained in this study since either no detailed hæmodynamic data are given or no spatial magnitudes were used. Only Wallace *et al.* (1962) have reported spatial magnitudes in aortic stenosis, the range of which is in keeping with results reported here. Yano and Pipberger (1964) have given evidence that spatial measurements show a close relation either to increase in systolic pressure determined in the systemic circuit or to radiologically determined heart size. Similar data were reported by A. N. Levy (personal communication, 1964), who showed a close relation between SMSV and the systolic pressure in patients with systemic hypertension. This present study provides a link with these observations and establishes the fact that at least in the "purified" situation of the child or young adult with congenital aortic stenosis, spatial electrical events recorded by the Frank system reflect closely the production of intraventricular systolic pressure. Further work will have to show whether these observations can be extrapolated to coarctation of the aorta or to adult patients with systemic hypertension or acquired aortic stenosis.

SUMMARY

A comparison was made of the accuracy of the vectorcardiogram, both uncorrected (cube) and corrected (Frank), and the standard electrocardiogram in the assessment of left ventricular hypertension in 30 patients with aortic stenosis. Peak pressure, gradient, valve area, and stroke work were used as reference points rather than heart weight or wall thickness.

There was a linear relation between left ventricular peak pressure and the maximum spatial vector ($r=0\cdot88$; $0<0\cdot001$) as well as the sum of selected spatial vectors ($r=0\cdot89$; $p<0\cdot001$). When the series was extended to 50 patients comparable coefficients were obtained ($r=0\cdot85$ and $0\cdot89$). Similar correlation with data derived by the cube system was less significant ($r=0\cdot72$ and $0\cdot75$ for 50 patients) while the sum of SV2 and RV5 yielded a coefficient of $0\cdot48$ and $0\cdot49$, respectively. All other hæmodynamic parameters gave less significant correlations and appeared not to reflect the electrical changes in a direct way. The usefulness of T wave changes was compared to alterations of the spatial QRS–T angle and the non-specificity of both was demonstrated, when used as an estimation of severity.

These results correspond to previous studies establishing the superiority of the Frank lead system above the cube system or standard electrocardiography and extend it to the assessment of left ventricular hypertension. They also indicate that measurement of specific spatial vectors permits the estimation of left ventricular peak pressure with a high degree of accuracy. Thus, in aortic stenosis in the adolescent and young adult age-group, this technique forms a worth-while adjunct in the assessment of its severity, which may reduce the need for indiscriminate cardiac catheterization.

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